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# Jet Observables and Stops at 100 TeV Collider

Collaboration with JiJi Fan, Prerit Jaiswal  
[10.1103/PhysRevD.96.036017](https://arxiv.org/abs/1704.03014) [[1704.03014](https://arxiv.org/abs/1704.03014)]

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# Motivation for a new collider

Once HL-LHC is done. What's next? **Discovery Machine: 100 TeV Collider**

- Give the final verdict on fine-tuning in SM, down to  $10^{-3}$ – $10^{-4}$ .
- Theoretical motivation... (Spannowsky, Neubert yesterday)
- An exploratory machine. For generic physics involving high mass states, a large centre of mass energy provides the most direct access to new physics!

[Arkani-Hamed, Han, Mangano, Wang, 1511.06495]

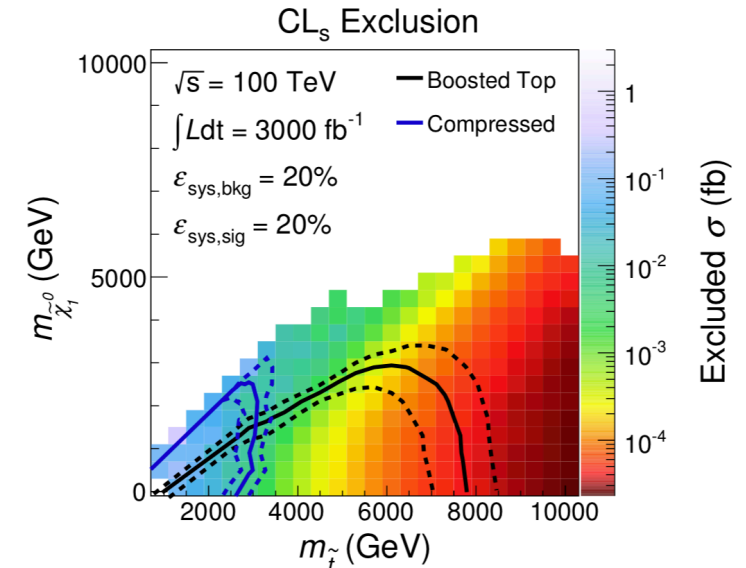
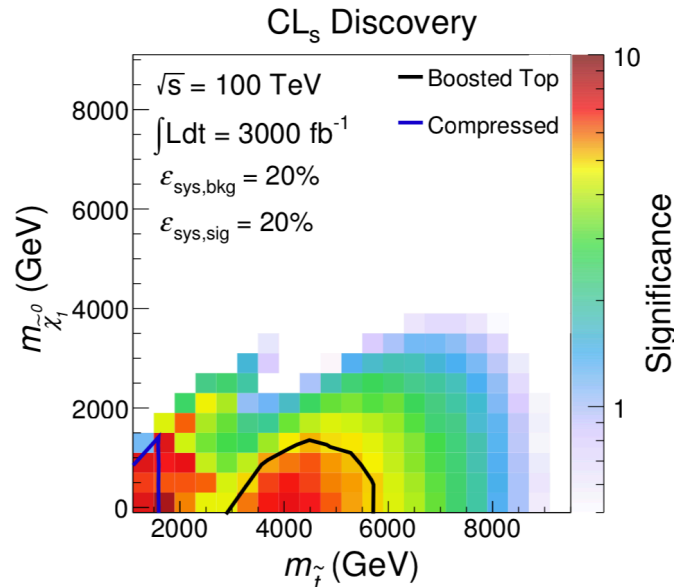
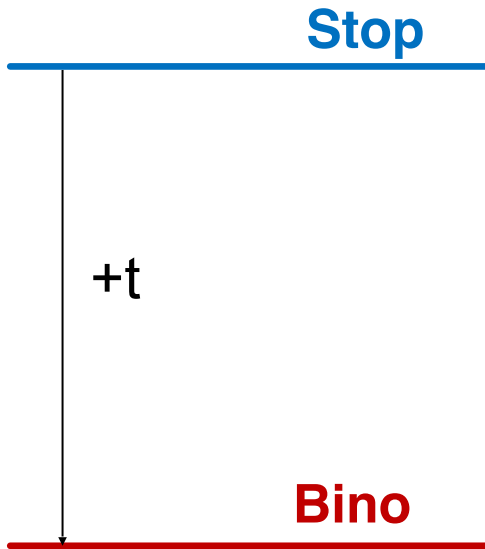
In a  $\sqrt{s} = 100$  TeV hadron collider,

Very hadronic environment;

SM objects are boosted and collimated.

→ Jet substructure techniques are needed to extract physics!

# Previous work

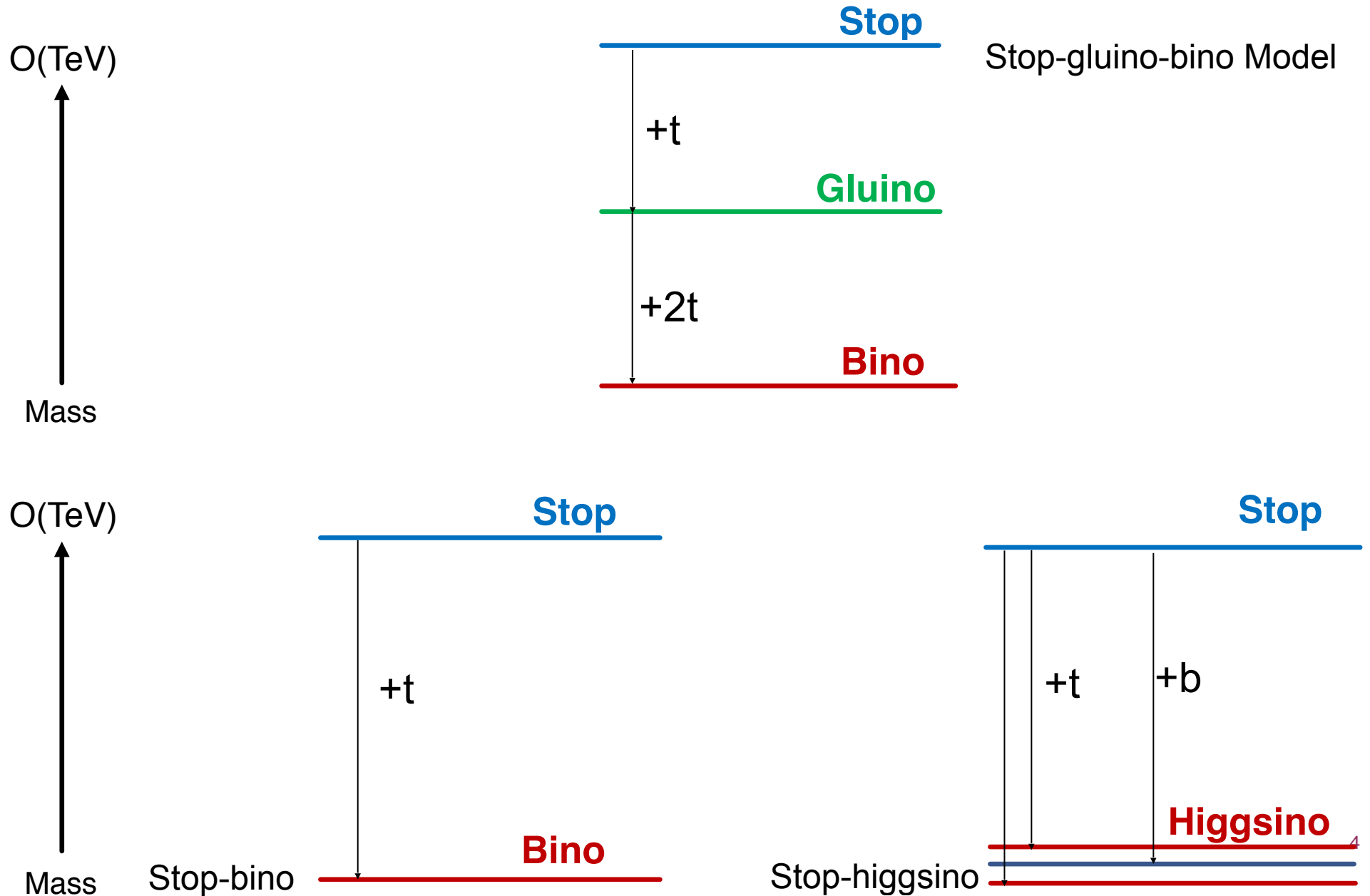


Previous study investigated simple stop-LSP model in  $\sqrt{s} = 100$  TeV collider using mostly kinematics variables.

[1406.4512, Cohen, D'Agnolo, Hance, Lou, Wacker]

We will investigate the reach of more complicated models with stop-gluino-LSP and higgsino LSP scenario.

# Simplified model's mass spectrum



# Method

## Cross-section:

SUSY process  $\rightarrow$  NLO + NNLL

SM process  $\rightarrow$  Madgraph LO

## Event generation:

Madgraph5  $\rightarrow$  Parton-level event

Pythia8  $\rightarrow$  parton-shower and hadronization

Delphes  $\rightarrow$  Detector

## SM Background:

QCD,  $t\bar{t}$ ,  $W/Z$  + jets,  $t + W/Z$  +2 jets

$t\bar{t} + W/Z$  +1 jet



$\tilde{t} - \tilde{g} - \tilde{\chi}^0$  Models

Stop

# stop-gluino-LSP model

+t

Gluino

Two production channels (stop-pair and stop-gluino associated)

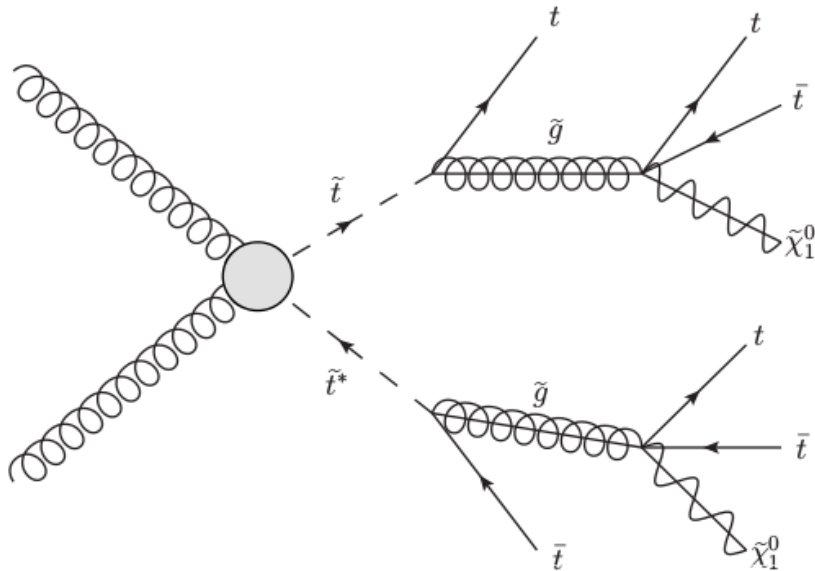
+2t

Bino

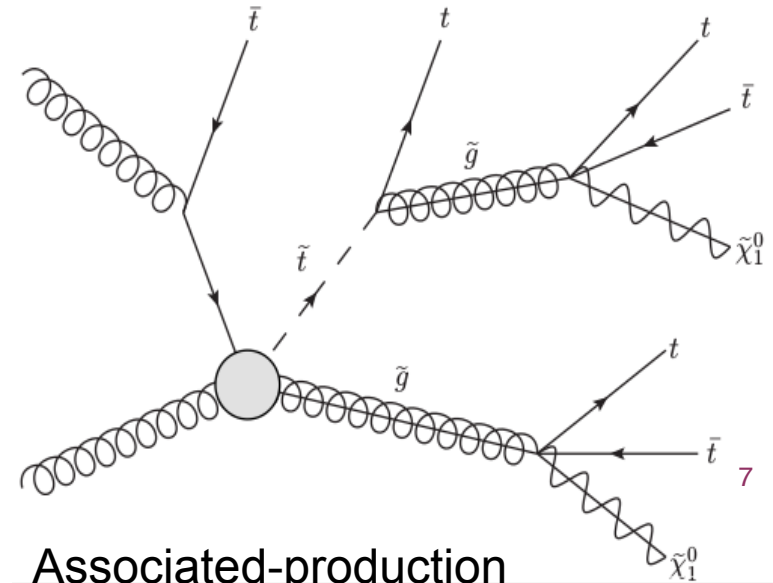
Final states: 6t + MET

The busy jet environment makes hard MET cut difficult

Stop-gluino-bino Model



Pair-production



Associated-production

# Cut Flow

## Kinematic cuts

(Schoenenberger, Weber Monday)

$$H_T > 4 \text{ TeV}, \text{MET} > 250 \text{ GeV}$$

No  $p_T > 35 \text{ GeV}$  isolated lepton

200 GeV jets  $> 6$  and ISRs ( $p_T$  hierarchy  $< 0.2$ ,  $|\eta| > 2$ )  $< 2$

$$|\Delta\phi(j, \cancel{E}_T)| > 0.5 \text{ for any jet with } p_T > 500 \text{ GeV}$$



$$\tilde{t}\tilde{t}^* + \tilde{t}\tilde{g} = 6.5\text{k events}$$

QCD =  $10^7$  events + other SM background!

Top-tagging ( $m_j, \tau_{3,2}, x_u$ )

Need hadronic top tag.



Refined HT and MET cut



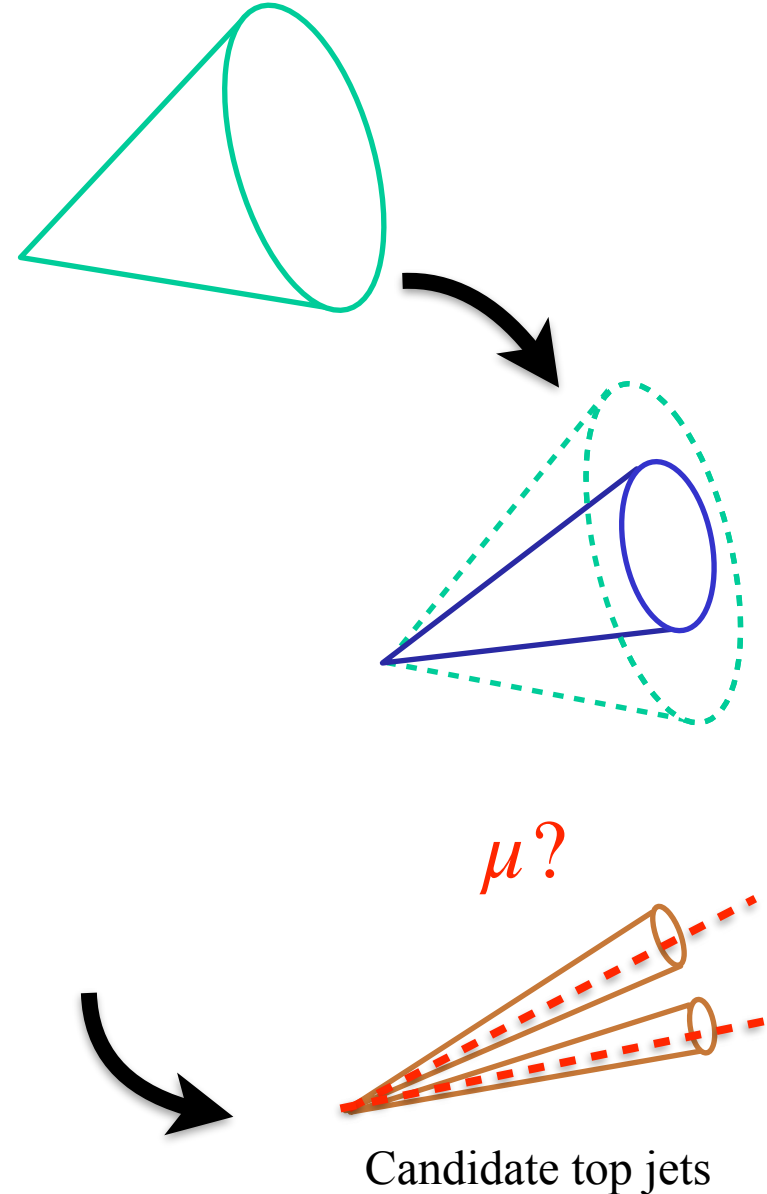
# Top-tagger and Jet clustering algorithm

[1503.03347, Larkoski, Maltoni, Selvaggi]

1. Cluster a C/A fat jet with  $R=1.0$
2. Scale down the jet by reclustering anti- $k_T$  jet with dynamical jet radius to remove radiation

$$R(p_T) = \frac{Cm_t}{p_T} \quad C \sim O(1) \text{ constant}$$

3. Look for  $p_T > 200$  GeV muon within the jet radius.  
If so,  $\rightarrow$  leptonic top tagger  
else,  $\rightarrow$  hadronic top tagger

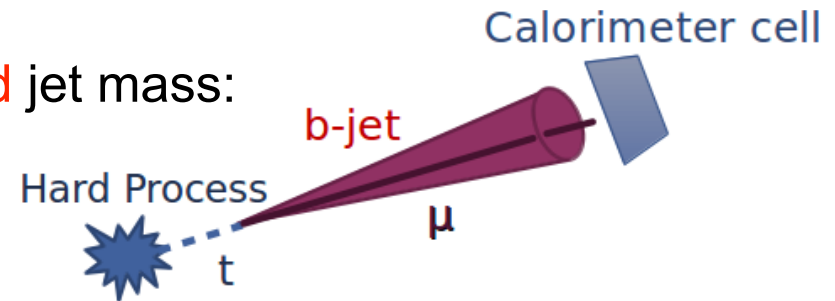


# Jet mass ( $m_j$ ) discriminant

Reconstructing the top mass from the **track-based** jet mass:

$$m_j = m_j^{(\text{track})} \frac{p_T^{(\text{total})}}{p_T^{(\text{track})}}$$

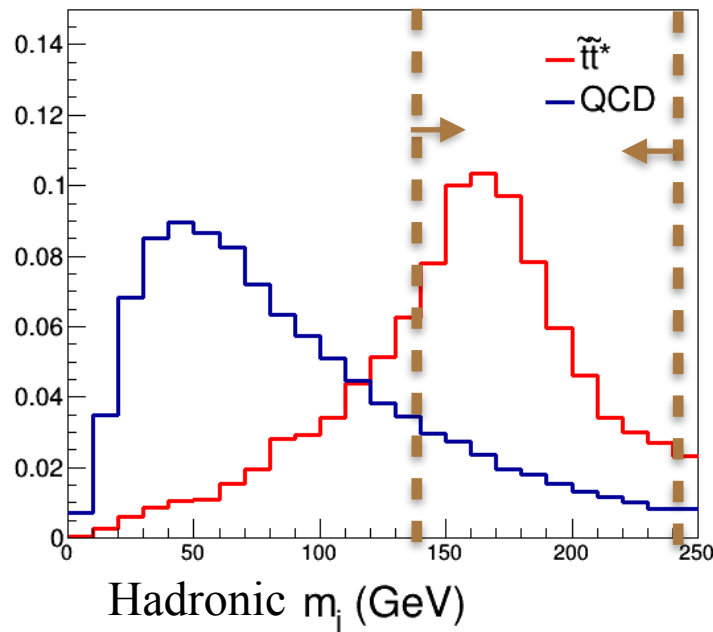
$m_j \approx m_{\text{top}}$  for a top jet



Calorimeter too small to resolve jet substructure!

## Hadronic top tagger

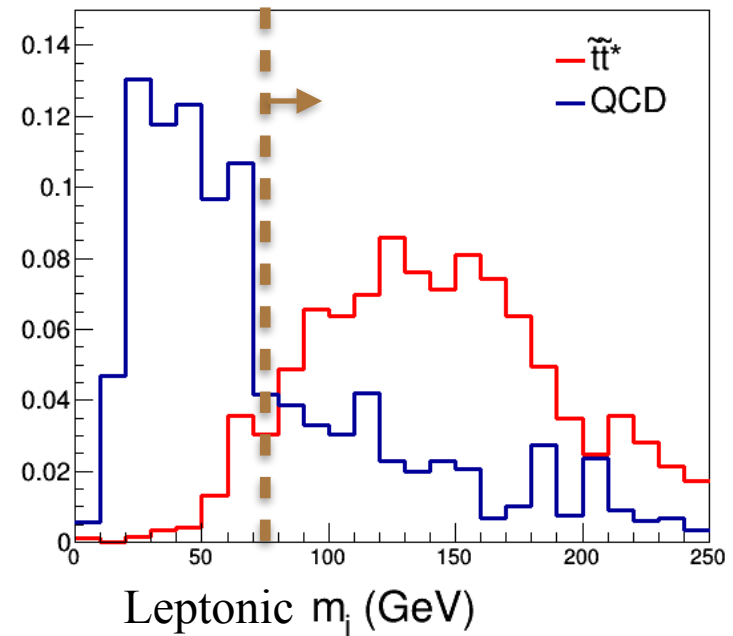
$140 \text{ GeV} < m_j < 240 \text{ GeV}$



## Leptonic top tagger

**MET from neutrino forbids complete mass reconstruction**

$m_j > 75 \text{ GeV}$

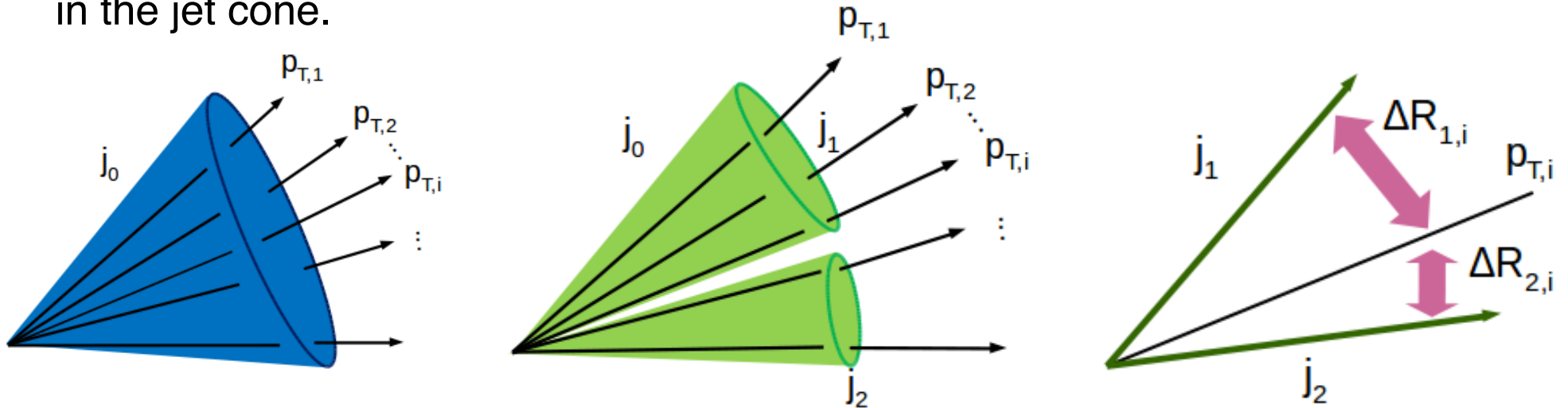


# Hadronic top-tagger: N-subjettiness ( $\tau_N$ )

[J. THALER AND K. VAN TILBURG, 11]

How much does jet “looks like” from a N-body decay?

N-subjettiness ( $\tau_N$ )  $\rightarrow$  how close are the jet constituents are from N sub-jet axes in the jet cone.



Identify the jet constituents to be reclustered



Recluster N subjets



Find the distance  $\Delta R_{k,i}$  between the  $i$ -th constituents and  $k$ -th subjet axis

$$\tau_N^{(\beta)} = \frac{1}{R_0} \sum_i p_{T,i} \min(\Delta R_{1,i}^\beta, \Delta R_{2,i}^\beta, \dots, \Delta R_{N,i}^\beta)$$

$p_{T,i}$  — transverse momentum of  $i^{\text{th}}$  jet constituent  
 $\Delta R_{k,i}$  — distance between  $k^{\text{th}}$  subjet and  $i^{\text{th}}$  constituent

# Hadronic top-tagger: N-subjettiness ( $\tau_N$ )

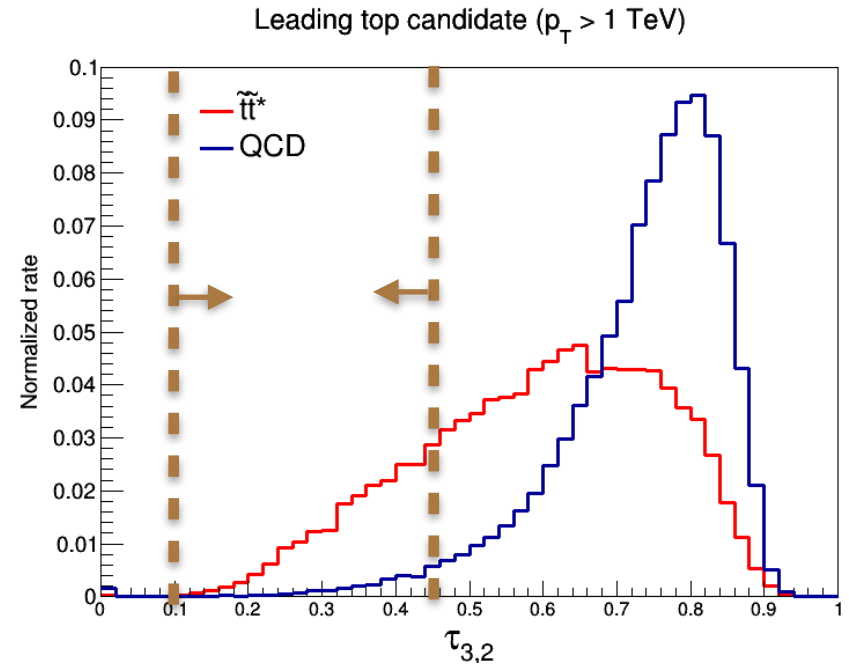
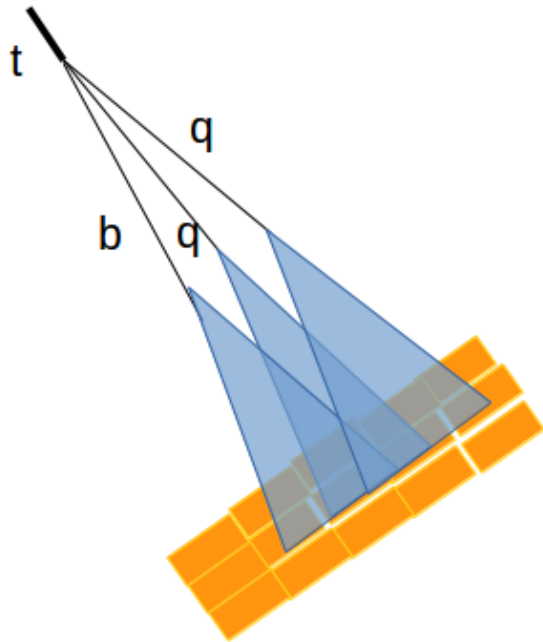
Hadronic top is a 3-prong object

$$t \rightarrow Wb \rightarrow q\bar{q}b$$

Top-jet will have small  $\tau_3$  and large  $\tau_2$ .

QCD jet will have evenly distributed  $\tau_3$  and  $\tau_2$ .

$\tau_3/\tau_2$  is a good discriminant variable.  $0.1 < \tau_3/\tau_2 < 0.45$  is the top-tag window.

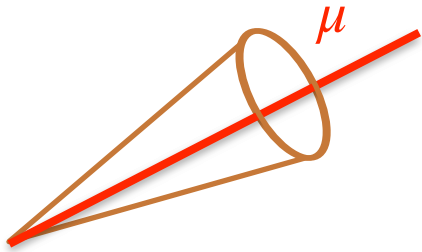


QCD vs hadronic top

# Leptonic top-tagger: Mass-drop ( $x_\mu$ )

[THALER AND WANG, 08; REHERMANN AND TWEEDIE, 11]

Leptonic top decays with a hard muon carrying a significant portion of energy-momentum  $t \rightarrow b\mu\nu$ . Mass-drop looks at the portion of muon contribution to jet-mass:



$$x_\mu = 1 - \frac{m_{j\mu}^2}{m_j^2}$$

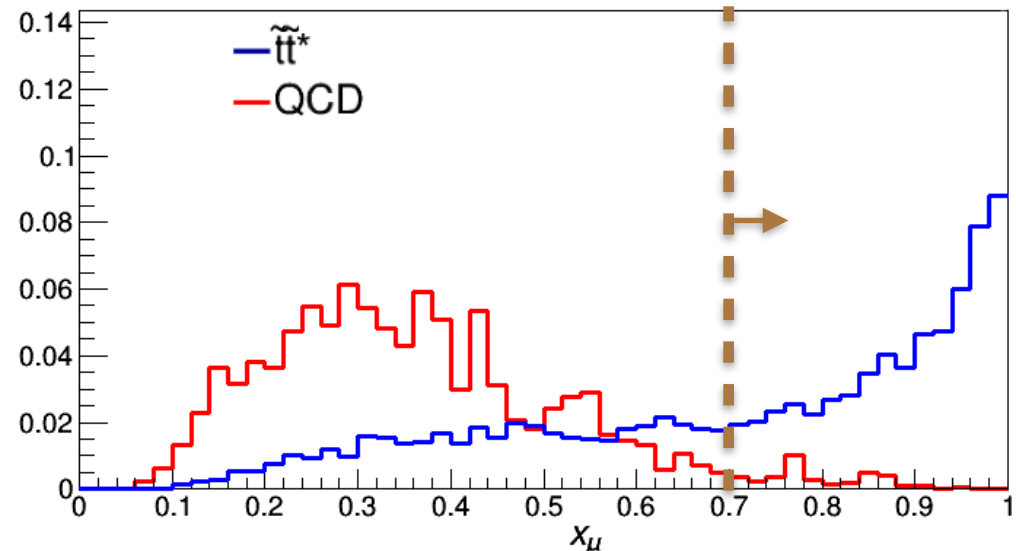
$m_j$  — full jet mass

$m_{j\mu}$  — jet mass without muon

Leptonic top will fail to reconstruct mass once muon is removed:  $x_\mu \rightarrow 1$ .

QCD jet mass does not tend to change since the muon is just a part of radiation.

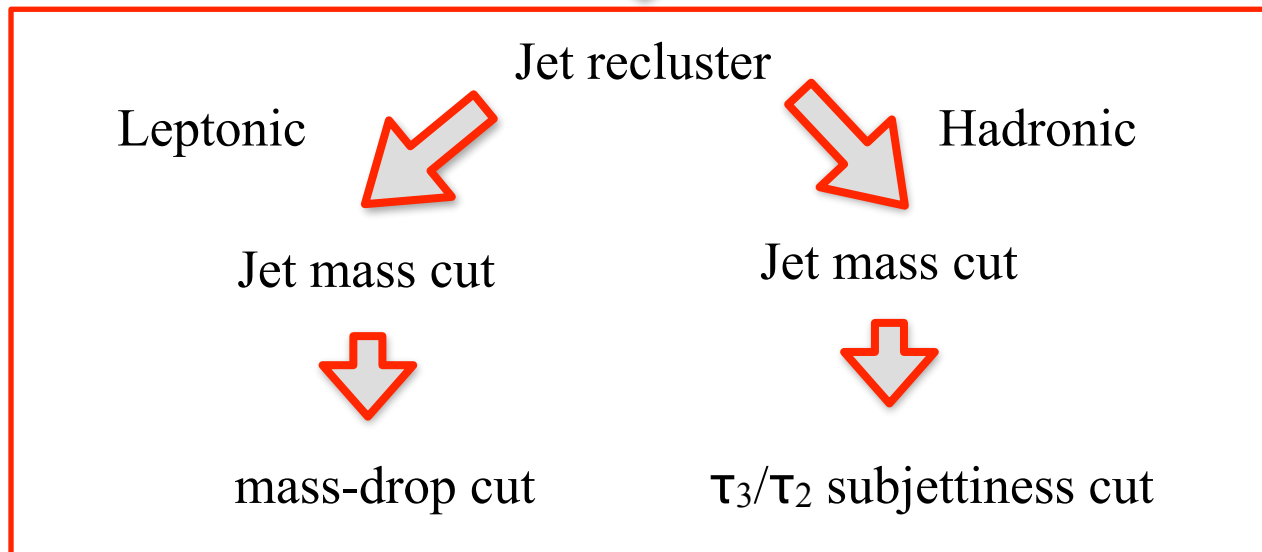
Acceptance is  $x_\mu > 0.7$



# Cut Flow Recap

$H_T > 4 \text{ TeV}$ ,  $\text{MET} > 250 \text{ GeV}$   
No  $p_T > 35 \text{ GeV}$  isolated lepton  
Number of jet and ISR cut  
 $|\Delta\phi(j, \vec{E}_T)| > 0.5$  for any jet with  $p_T > 500 \text{ GeV}$

**Kinematic cuts**



**Top-tagger X 3**

Refined  $H_T$  and MET cut

# Stop mass reach

$m_{\tilde{t}}$ (TeV)	S	B	$\sigma$
5.5	10.7	1.7	6.3
6.0	10.0	6.7	3.5

10% systematics

$3\sigma$  can be reached for the benchmark point of 6 TeV stop and 2.75 TeV of gluino at  $L = 30 \text{ ab}^{-1}$ .

An increased L is needed due to high the high SUSY background.

# Gluino mass Reach

A gluino mass reach to 11 TeV at  $L = 3 \text{ ab}^{-1}$  (pair-production channel).

$m_{\tilde{g}}$ (TeV)	Top tags	S	B	$\sigma$
10.0	2	12.4	0.8	8.1
11.0	1	13.8	9.5	3.9

10% systematics

$\sim 2 \text{ TeV}$  improvement compared to the same sign Di-lepton gluino search in [1311.6480].

$\tilde{t} - \tilde{B}$  Model and  $\tilde{t} - \tilde{H}$  Model



# Search Strategy Stop-Bino/Higgsino

**Stop**

**Stop**

Which one is the signal?



**Bino**

**Higgsinos**

$$\tilde{t} \longrightarrow t\tilde{\chi}_1^0$$

$$\tilde{t} \longrightarrow b\tilde{\chi}^\pm \longrightarrow b\tilde{\chi}_1^0 j^{(\text{soft})}$$

$$\tilde{t} \longrightarrow t\tilde{\chi}_2^0 \longrightarrow t\tilde{\chi}_1^0 j^{(\text{soft})}$$

$$\tilde{t} \longrightarrow t\tilde{\chi}_1^0$$

- The environment is clean. Hard MET cut is possible.
- Stop-bino model always decay to top.
- Stop-higgsino model decay 50% of time to top and 50% to bottom

# Search Strategy Stop-Bino/Higgsino

Two anti- $k_T$  jets with  $p_T > 1$  TeV;  
No isolated lepton with  $p_T > 1$  TeV;  
 $|\Delta\phi(j, \cancel{E}_T)| > 0.5$  for any jet with  $p_T > 500$  GeV;  
MET  $> 3$  TeV

**Kinematic cuts**



Muon  $p_T > 200$  GeV inside one of the jets



Muon-in-jet does not select leptonic top.  
Boosted b-jet also contains hard muons!

Further selection on hadronic jets needed!

**Boosted top / b-jet tagger**

# Search Strategy Stop-Bino/Higgsino

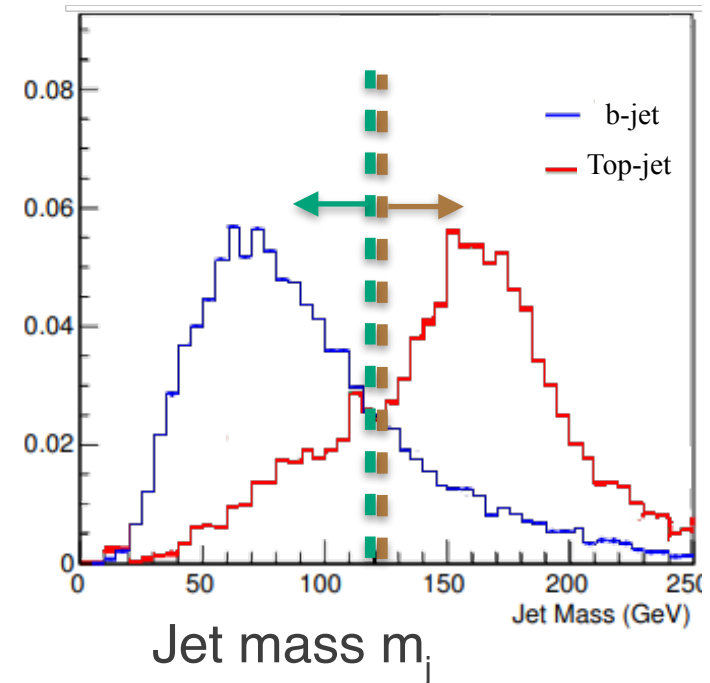
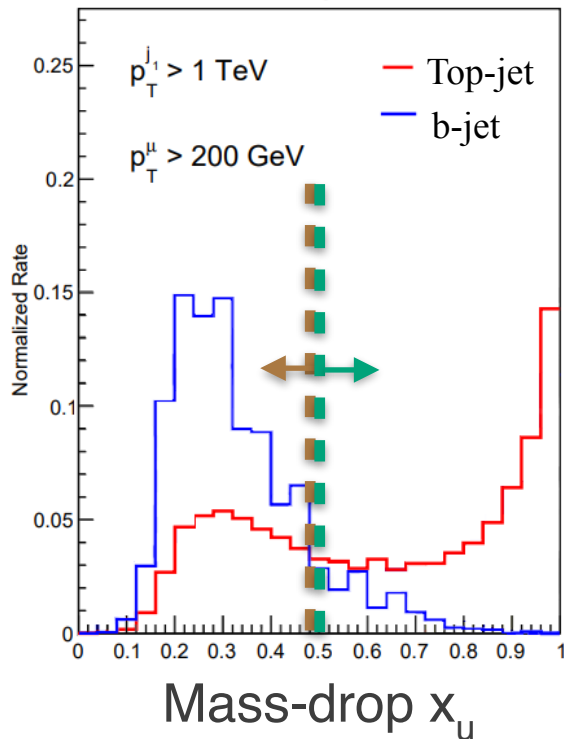
After passing through the muon-in-jet requirement. We partition the events into two possibilities using jet mass and mass-drop:

**Boosted top jet** ( $\tilde{t} \longrightarrow t\tilde{\chi}^0$ ):  $m_j > 120$  GeV **OR**  $x_u > 0.5$

**Boosted b-jet** ( $\tilde{t} \longrightarrow b\tilde{\chi}^\pm$ ):  $m_j < 120$  GeV **AND**  $x_u < 0.5$

Hadronic top jet

Leptonic top jet



The stop-bino and stop-higgsino model signature differs in the b-jet signature.

We define the variable

$$r_- = \frac{N_b - N_t}{N_b + N_t}$$

$N_b$  = # of boosted b-tagged events

$N_t$  = # of boosted top-tagged events

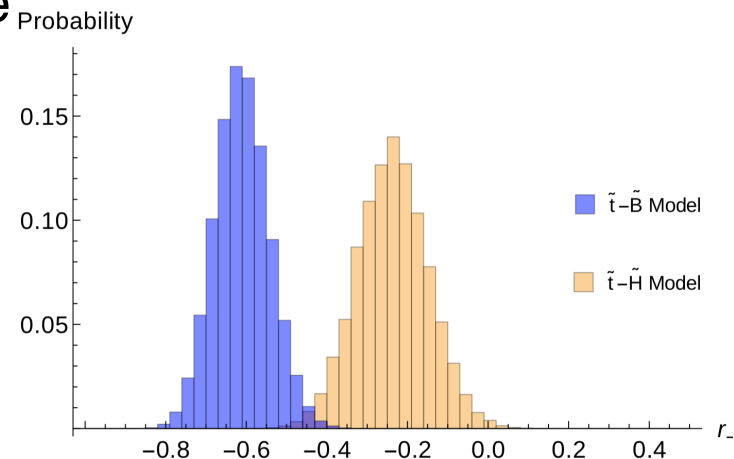
Stop-higgsino has 50% b-jet and 50% top jet.

$r_- \sim 0$

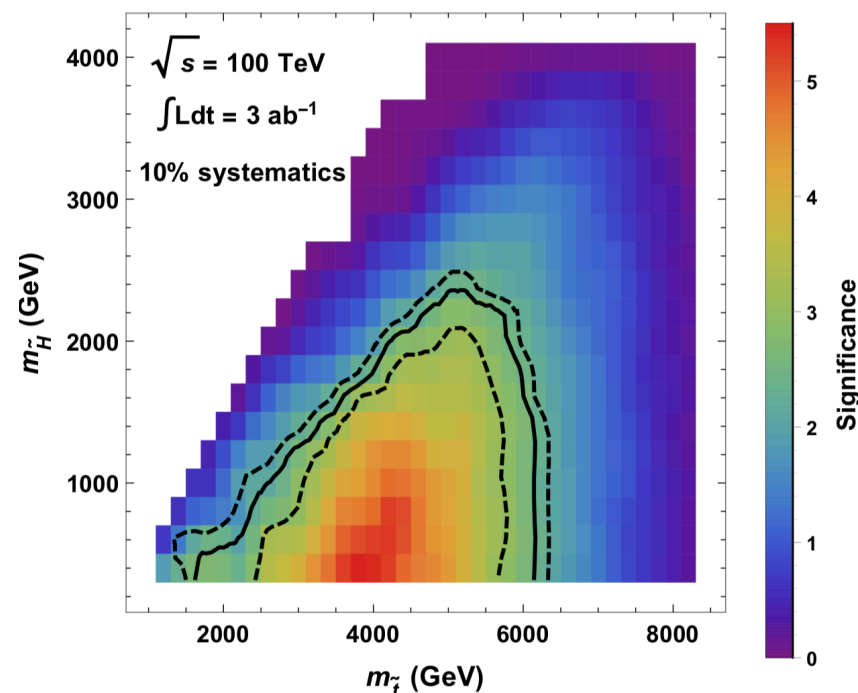
Stop-bino 100% top jet. Hence  $r_- \sim -1$

Model-distinguishability Reach:

$$\{m_{\tilde{t}} \sim 6 \text{ TeV}, m_{\tilde{\chi}} \sim 2 \text{ TeV}\}$$



$r_-$  distribution over the life time of the experiment



95% confident level

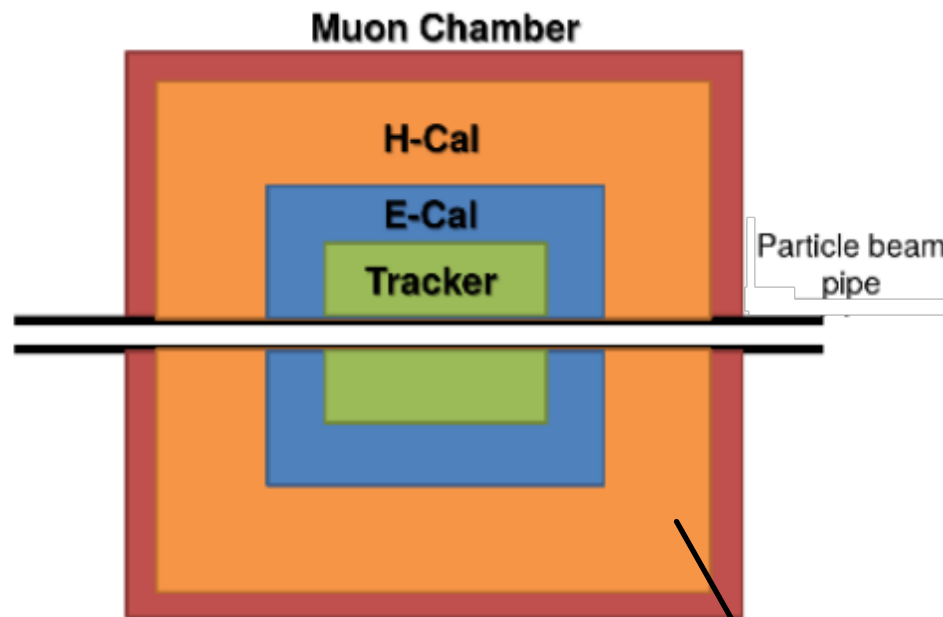
# Summary and future work

- Stop-Gluino-LSP model mass reach 6 TeV ( $L = 30 \text{ ab}^{-1}$ ). Gluino mass reach 11 TeV ( $L = 3 \text{ ab}^{-1}$ ). Stop-Bino/Higgsino discovery mass reach at 7 TeV, model identification reach at 6 TeV ( $L = 3 \text{ ab}^{-1}$ ). Yet to be improved by BDT, NN and various other observables!
- A 100 TeV collider will extend our understanding to the naturalness of Standard Model and help exploring new physics.
- Jet substructure technique is a necessary and powerful tool to extract physics from a 100 TeV collider. Help make the case for future colliders.



# Back-up Slides

# Detector design



A common design for a particle detector

30 cells in  $|\eta| < 2.5$ , 5-10 deg per cell

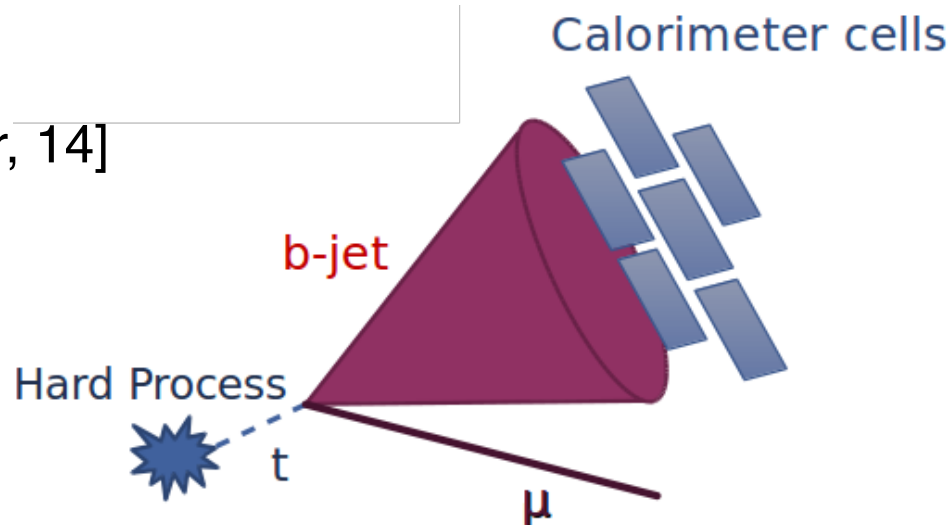
# Boosted Object Challenges

[Cohen, D'Agnolo, Hance, Lou, and Wacker, 14]

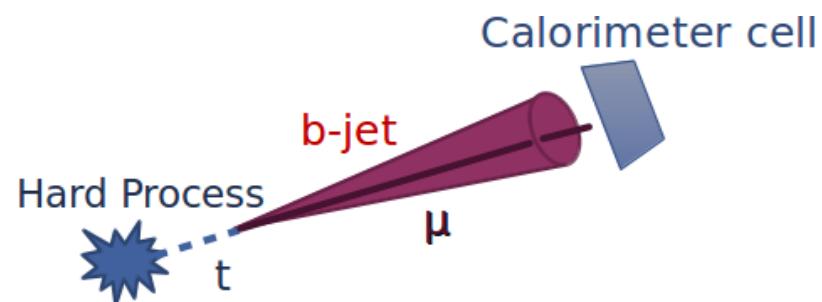
- At high luminosity, the high Standard Model event rate can conceal new physics.

- At high energy, SM objects are boosted. Different objects are collimated along the boost direction, to a point they are smaller than a calorimeter cell.

- New jet substructure techniques are needed.



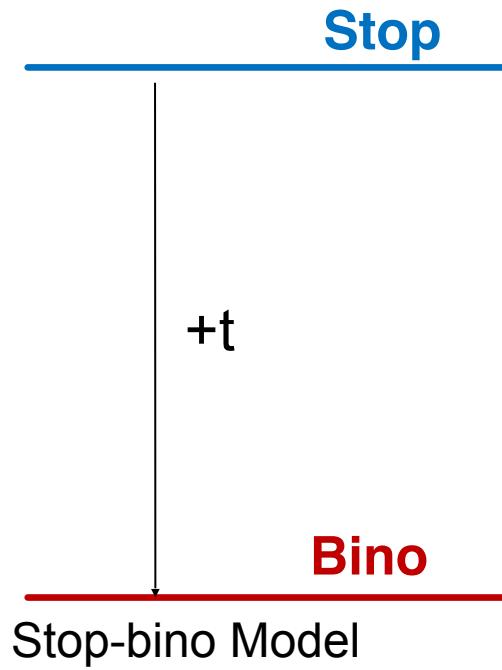
A top quark decaying in the LHC



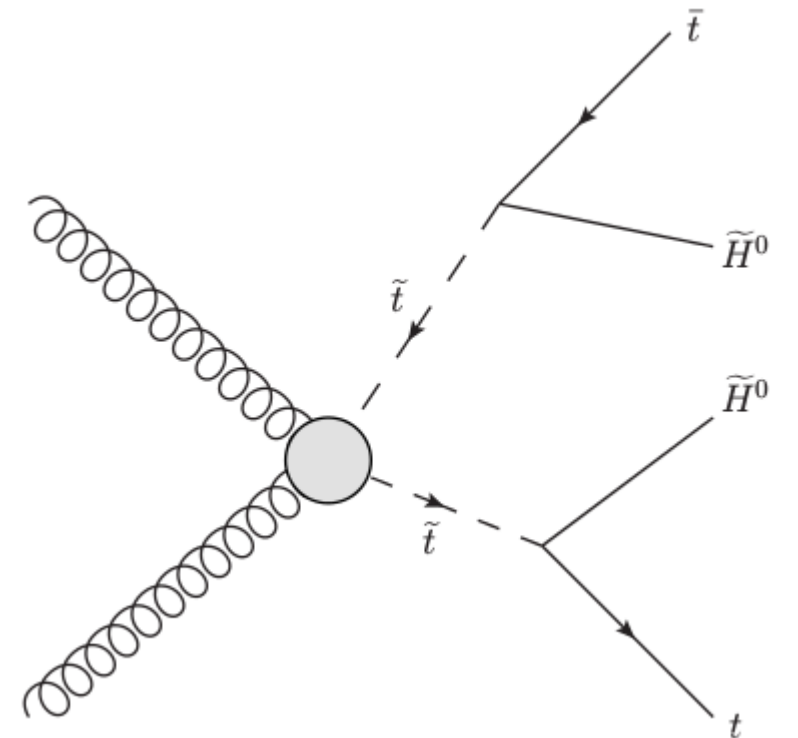
A boosted top in a 100 TeV collider



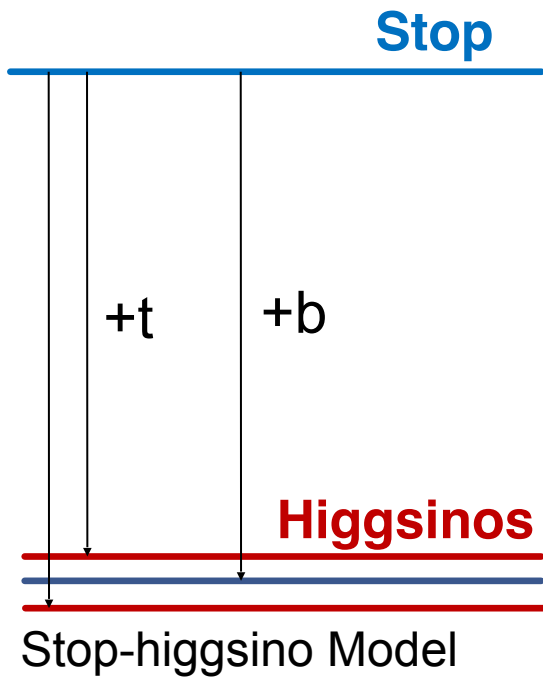
# stop-bino model



Final state:  $t\bar{t}$  + MET

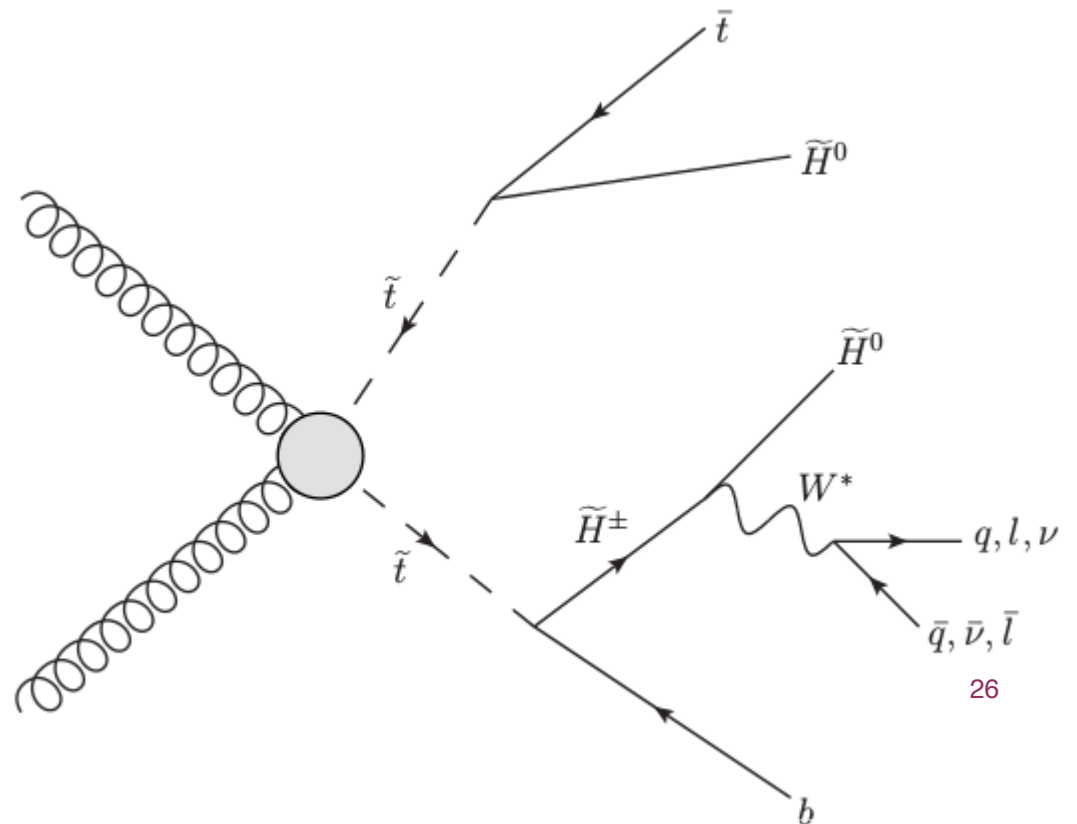


# stop-higgsino model



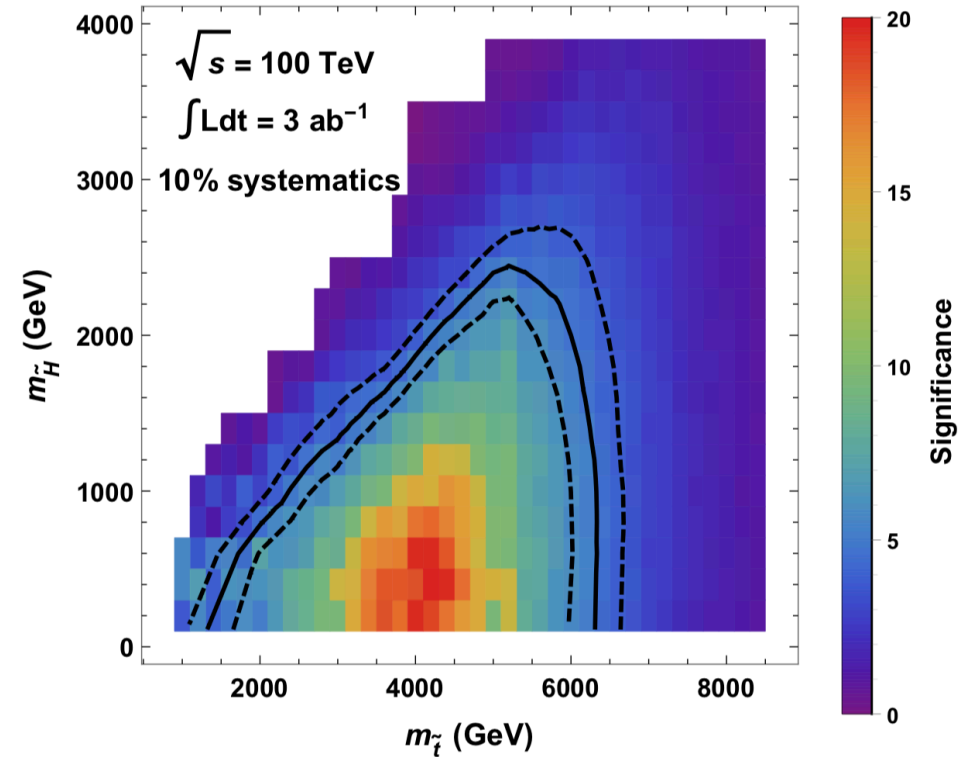
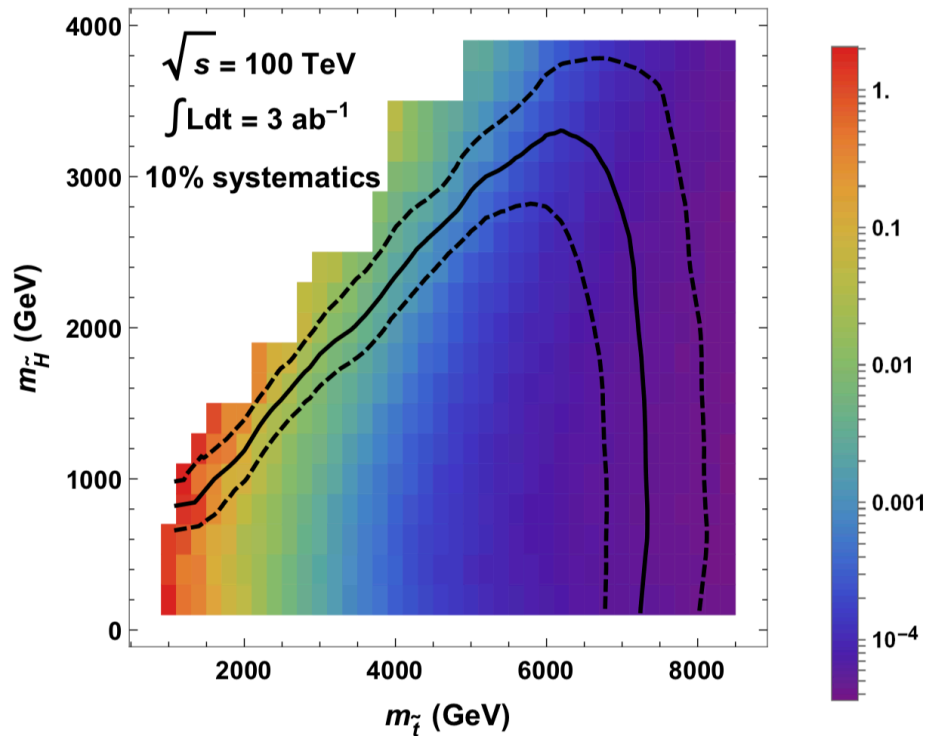
- $\tilde{t}$  50% decay to t + MET
- $\tilde{t}$  50% decay to b + MET

Final states: combinatoric of both



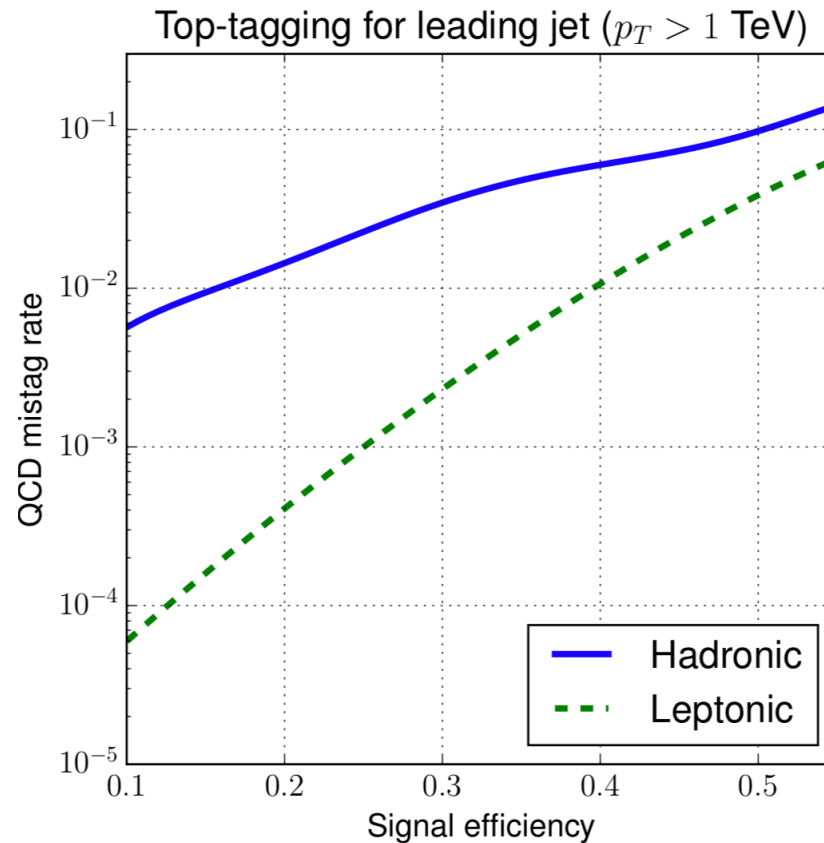
# Stop-higgsino Mass Reach

The discovery/exclusion contours for stop-higgsino model with an integrated luminosity  $L = 3 \text{ ab}^{-1}$ .



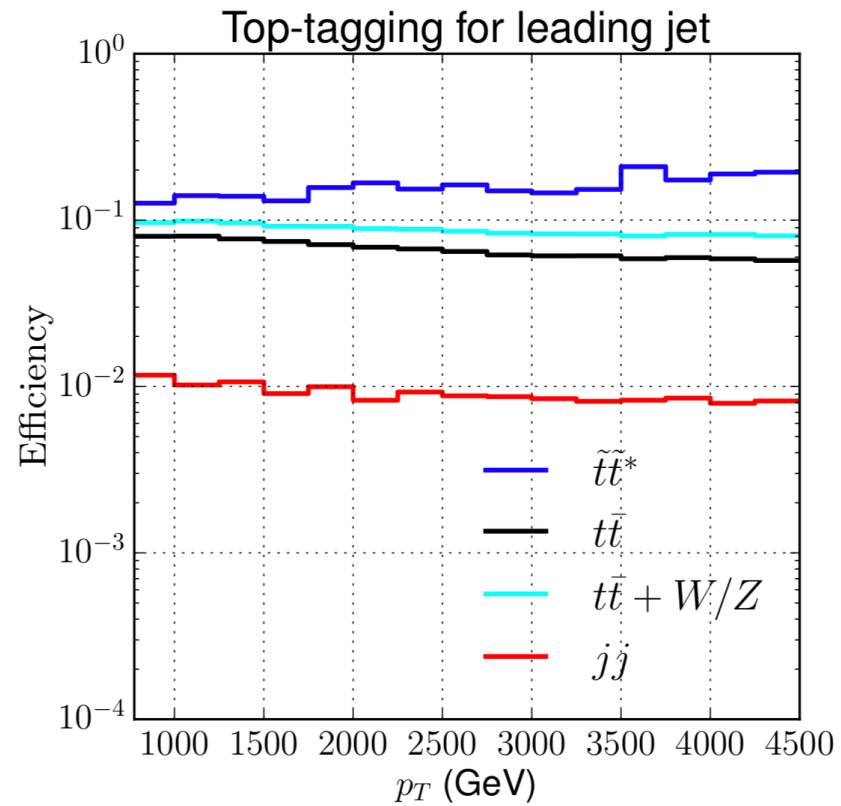
The solid lines are  $5\sigma$  discovery contour (left) and exclusion at 95% C.L. (right). The dashed lines are the  $\pm 1\sigma$  boundaries.

# Tagging Efficiency



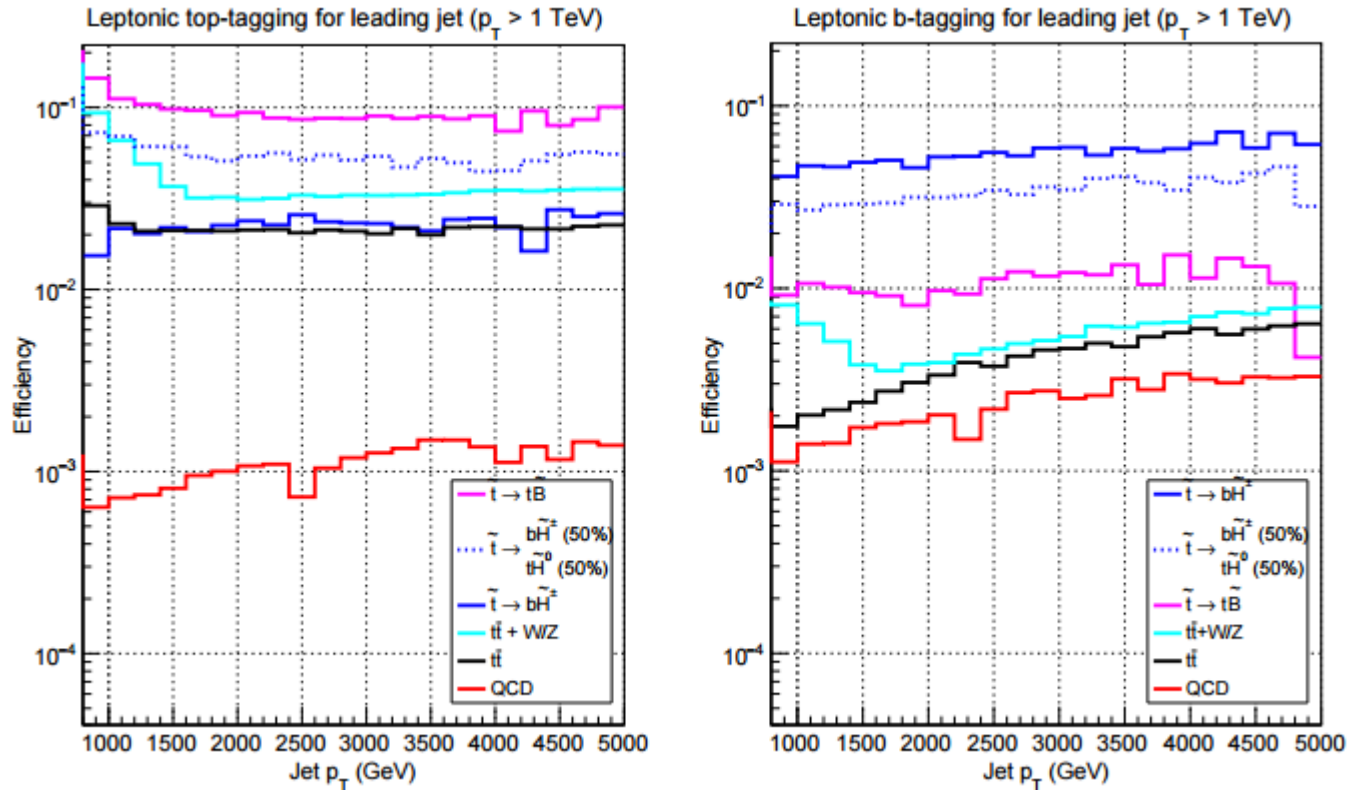
QCD mistag vs signal efficiency

# Tagging Efficiency



Signal/background efficiencies top-tagging

# Efficiency



Signal/background efficiencies for stop-higgsino cut